

SMART HANDS FOR THE EVA RETRIEVER

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ABSTRACT

Dexterous, robotic hands are required for the extravehicular activity retriever (EVAR) system being developed by the NASA Johnson Space Center (JSC). These hands, as part of the EVAR system, must be able to grasp objects autonomously and securely which inadvertently separate from the Space Station. Development of the required hands was initiated in 1987. This paper outlines the hand development activities, including design considerations, progress to date, and future plans. Several types of dexterous hands that were evaluated, along with a proximity-sensing capability that was developed to initiate a reflexive, adaptive grasp, are described. The evaluations resulted in the design and fabrication of a 6-degree-of-freedom (DOF) hand that has two fingers and a thumb arranged in an anthropomorphic configuration. Finger joint force and position sensors are included in the design, as well as infrared proximity sensors which allow initiation of the grasp sequence when an object is detected within the grasp envelope. This hand design is being integrated with the JSC EVAR test bed and will be evaluated in the near future.

INTRODUCTION

Future space operations could benefit from a highly autonomous robot that is capable of assisting an extravehicular activity (EVA) crewmember. In addition to providing increased productivity for a given human crew complement, highly autonomous robots could also be substituted for the human crewmembers for certain hazardous EVA tasks. As a first step in the evolution of this type of robot, the Engineering Directorate at Johnson Space Center (JSC) has undertaken a project to develop the EVA retriever (EVAR), which is a highly autonomous, free-flying robot that is intended to retrieve items which inadvertently separate from the Space Station Freedom [1] [2] [3]. Figure 1 illustrates the retrieval activity. This project is currently in the ground demonstration stage, which consists of developing a test bed version of the EVAR system to investigate requirements and issues associated with building a flight-rated system that can be flown on the Space Shuttle as a flight experiment.

A key element of the EVAR system is the Smart Hand. A Smart Hand is a dexterous robotic hand that will allow autonomous grasping operations much like an EVA crewmember would use when retrieving an item. This type of hand will allow a dexterous grasping capability to be established and demonstrated for the EVAR that can then be evolved in the future to provide manipulative capability for follow-on generations of robots. This paper outlines the EVAR Smart Hand development, including objectives, approach, implementation, and future plans.

OBJECTIVES

The development effort is focused on two objectives: (1) to develop advanced technologies required to provide autonomous, adaptive grasping capability for the EVAR, and (2) to develop a ground demonstration of the Smart Hand concept and capabilities.

Based on operating conditions and interface requirements, the following six major performance goals are desired:

- (1) Utilize ability to grasp objects without any prior knowledge of them - If the separated item is defaced or broken, a model-based grasp algorithm which requires prior knowledge of the item would most likely fail. Therefore, a non-model based approach is required.
- (2) Utilize autonomous, adaptive grasping capability - The grasp action should be adaptive and autonomous, requiring only high-level commands to initiate the grasp action. This will free the central computer from having to perform low-level control tasks.
- (3) Utilize same tool and equipment interfaces used by an EVA crewmember - By utilizing the same tool and equipment interfaces as used by an EVA crewmember, the need to develop special tool and equipment interfaces for the robot is minimized.
- (4) Approximate EVA crewmember hand size and dexterity - By designing the robotic hand to have the same size and dexterity as that of an

EVA crewmember, the hand is compatible with the interface specified in (3).

(5) Maximize reliability - High reliability for the robotic hand contributes to a greater potential of mission success and also reduces the need for difficult, expensive EVA maintenance and repair.

(6) Minimize mass - Excessive mass in the robotic hand can create a large inertial load for the motors in the arms and hands, thereby reducing the dynamic response of the robot. Minimizing the mass will also reduce the propulsion fuel requirement. Since the EVAR is propelled by the manned maneuvering unit (MMU), minimizing the hand mass will also reduce the MMU propellant requirement.

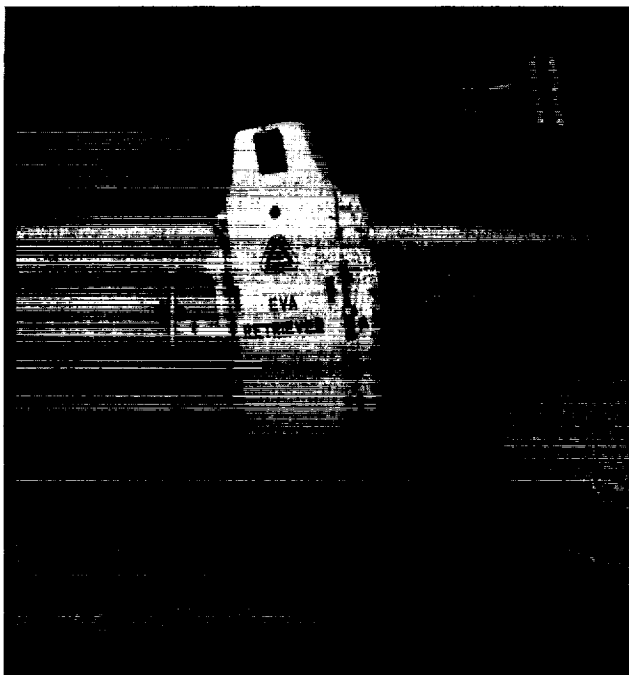


Figure 1.- EVAR concept.

APPROACH

The approach taken is as follows:

- Procure and evaluate commercially available, state-of-the-art dexterous robotic hands technologies and develop in-house expertise. By understanding the features of existing hands, it was not necessary to re-invent the technologies already developed by other institutions.

- Develop and evaluate robotic hands in-house. In-house design concepts were fabricated and evaluated to provide alternate hand configurations that were compared with the commercially available robotic hands.

- Develop and evaluate sensors and control systems. Sensors and control systems are two important components in an autonomous robotic hand system. Advanced sensor systems were also developed for different hands to provide position and force controls.

- Derive an optimized EVAR Smart Hand design based on evaluation results and performance goals. Each robotic hand was evaluated with the performance goals in mind. A design which came closest to meeting the performance goals was developed by incorporating features found in commercial and in-house developed robotic hands.

- Integrate prototype hands with the EVAR test bed system and demonstrate the EVAR Smart Hand capability to operate in a dynamic environment as part of an integrated system. When completed, this activity will provide an understanding of the multiple-body dynamics and hand-arm coordination associated with the EVAR scenario.

DISCUSSION

The following discussion describes the implementation of the approach outlined above.

A. Procure and evaluate commercially available robotic hands

Two commercially available dexterous robotic hands were procured for evaluation: the Utah/Massachusetts Institute of Technology (MIT) hand and the Stanford/Jet Propulsion Laboratory (JPL) hand. These two hands represent the state-of-the-art in dexterous hand capabilities. The capabilities of each hand are described below.

Utah/MIT Hand

The Utah/MIT hand is the most dexterous hand in the spectrum of hands available for our evaluation. The Utah/MIT hand system is shown in Figure 2. The hand has 16 degrees-of-freedom (DOF) arranged in an anthropomorphic configuration of three fingers and a thumb. The fingers and the thumb each have 4 DOF. Thirty-two pneumatic actuators operating at pressures up to 80 psi provide power to the hand. Tendons are used to transmit power from these pneumatic actuators to the joints through a system of pulleys and linkages called a "remotizer." Each joint is controlled by a pair of antagonistic tendons. Located inside each joint is a linear Hall effect sensor that measures the joint angles. Hall effect sensors are also located in the wrist to monitor the tendon tensions. A control box containing analog feedback control circuitry provides manual control of each joint with an interface for computer control that can be used in lieu of manual control [4].

Stanford/JPL Hand

The Stanford/JPL hand, designed by Dr. J. Kenneth Salisbury, is a 9-DOF hand with a non-anthropomorphic finger configuration and a large



Figure 2.- Utah/MIT dexterous robotic hand system.

envelope of excursion. The hand has three fingers, each with three joints. The joints are driven by a set of metal cables that transmits mechanical power from 12 remotely located direct current (DC) motors equipped with position encoders. Located behind the proximal joint of each finger are four strain gauges that measure the cable tensions. The tension signal may be translated into a joint torque signal which is used in the servo control. The fingertips of the Stanford/JPL hand are made of a highly compliant material that provides the friction contact necessary for a secure grasp. Figure 3 shows the Stanford/JPL hand and its remote motor package.

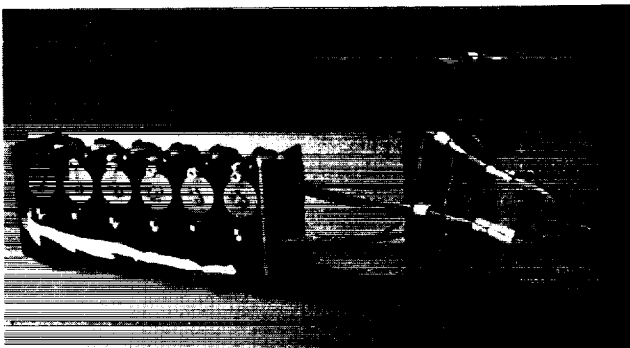


Figure 3.- Stanford/JPL hand system.

B. Develop and evaluate robotic hands in-house

The NASA/JSC Crew and Thermal Systems Division (CTSD) I hand and the CTSD II hand were both developed by CTSD to evaluate in-house design concepts. The CTSD I hand was built in 1987 to support the Phase I EVAR ground demonstration system. The CTSD II hand will replace the CTSD I hand on the Phase II EVAR ground demonstration system. Also available for evaluation is the

Direct Link Prehensor, a human-operated hand originally developed by NASA/Ames Research Center (ARC) and Stanford University for space suit applications. It has two fingers and a thumb in an anthropomorphic arrangement. A modified version of it was built at JSC. The important features of these hands are described below.

CTSD I Hand

The CTSD I hand has three fingers driven by a single DC motor. The three fingers are spaced 120 degrees apart, and they open and close simultaneously. Each finger contains three sections connected by joints. The sections are coupled by direct linkages; therefore, the push-pull motion created by the rod inside the proximal finger section will cause the other sections to move also. As the fingers begin to close, the distal finger section will bend around the object and trap the object within the grip of the hand for a secure grasp. The motions of the three fingers are also coupled by a cable-pulley system, so when any one finger is forced to stop, the other two will continue to close until all three fingers have stopped. These mechanisms are shown in Figure 4. Although this hand is a step beyond the simple parallel jaw gripper, it still has some drawbacks. The hand does not have enough independently controlled, articulated joints to allow alternate grasp arrangements, and it lacks sufficient sensory feedback to provide adequate information about the grasp quality.

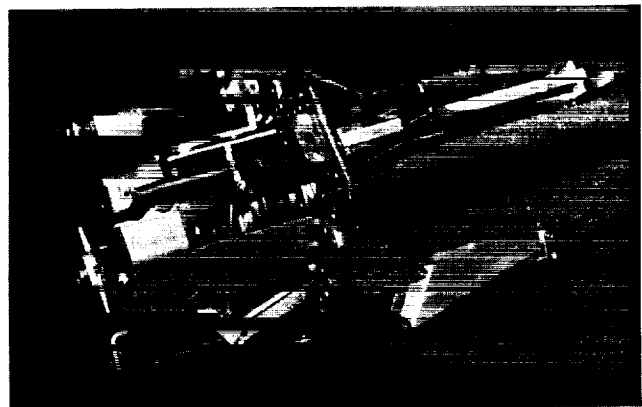


Figure 4.- CTSD I hand.

CTSD II Hand

Like its predecessor, the CTSD II hand also has three fingers. However, there are several important differences. The fingers of the CTSD II hand are arranged in a two-opposing-one configuration to provide parallel grasping surfaces. This finger configuration is able to adapt to different shapes of objects better than the CTSD I hand configuration. The CTSD II hand is also designed with modular fingers. If additional fingers are required, they may be added without creating an impact on the overall design. Each finger is driven by one DC motor contained within the finger module. Tactile sensors and strain

gauges on each finger provide added sensory feedback [5] [6]. Silicon pads cover the tactile sensors for protection and provide a compliant, friction surface for a more secure grasp. The maximum amount of force each finger can exert is controlled by current-limiting circuitry in the control electronics.

A 2-DOF wrist has been designed to complement the CTSD II hand. With its two drive motors and differential gearing, the wrist is capable of simultaneous pitch and yaw. Encoders are mounted on the wrist motors for position feedback. Together with the CTSD II hand, the hand-wrist combination provides a total of 5 DOF and a fairly large working envelope. The hand and the wrist are currently being integrated with the Phase II EVAR ground demonstration unit for dynamic evaluation. Figure 5 shows the CTSD II hand-wrist-forearm assembly.

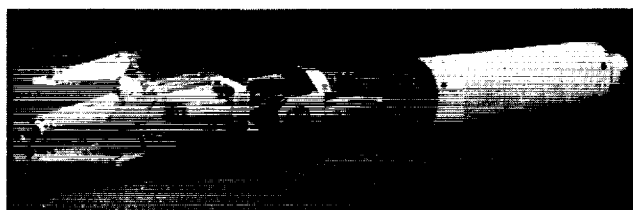


Figure 5.- CTSD II hand-wrist-forearm assembly.

Direct Link Prehensor

The Direct Link Prehensor, as shown in Figure 6, was originally developed by NASA/ARC and Stanford University to function as a space suit end effector that fits over the hand like a glove. The prehensor has a total of 6 DOF in an anthropomorphic configuration. It has two fingers and a thumb, with the thumb opposing the two fingers at an angle to provide grasping capability as well as some manipulation capability. The mechanical fingers are directly coupled to their human counterparts through a mechanical linkage system. The prehensor has been flown on the NASA KC-135 aircraft to evaluate grasping in a weightless environment using a mechanical hand [7]. The result of this study helped to focus the EVAR Smart Hand development by providing data on the speed and sensing requirements as well as assisting in the planning of grasp strategies. The prehensor has also been a valuable tool in tactile sensor development. Tactile sensors have been integrated with the prehensor to study sensor characteristics, sensor installation techniques, and selection of sensor sites.

C. Develop and evaluate sensor and control systems

Proximity Sensor

The concept of adaptive grasping has been demonstrated with the Utah/MIT hand using position, force, and proximity sensors. Two layers of proximity sensors have been installed on the Utah/MIT hand. The first layer consists of one reflective infrared (IR) sensor mounted in each fingertip. Sensors in this layer provide approach

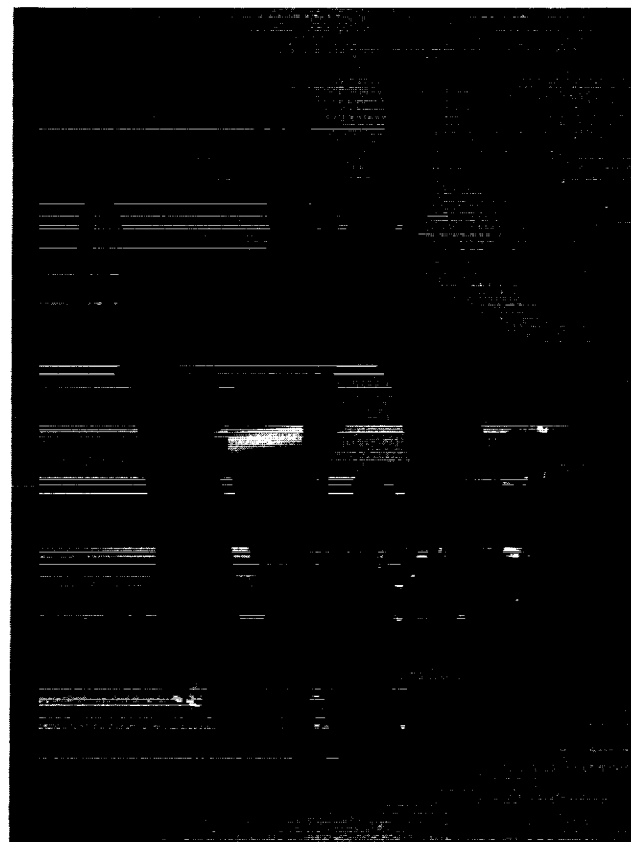


Figure 6.- Direct-Link prehensor.

axis alignment as the robotic hand approaches an object during grasping. The second layer consists of the same type of sensors mounted in the middle segment of each finger, and they are used to trigger the closing of hand. Figure 7 illustrates the adaptive grasping concept. The proximity sensors currently being used are miniature reflective IR sensors made by TRW. Each sensor, as shown in Figure 8, has a transmitter and a receiver colocated on a chip with an area of $0.75 \text{ cm} \times 0.75 \text{ cm}$. The small size allows them to be installed on most robotic hands. Special signal conditioning circuits have been built to provide power, modulation, gain, and filtering of the sensor signals. With a sufficient number of proximity

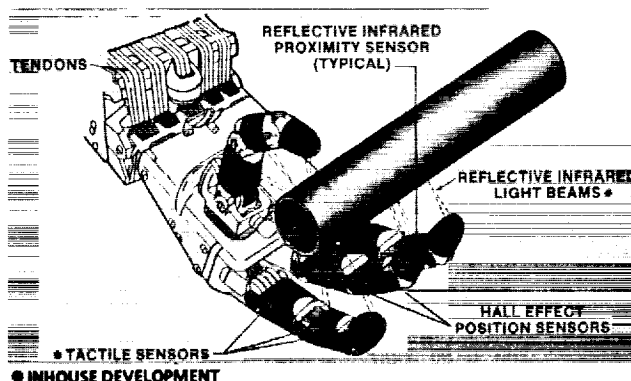


Figure 7.- The Utah/MIT dexterous robotic hand.

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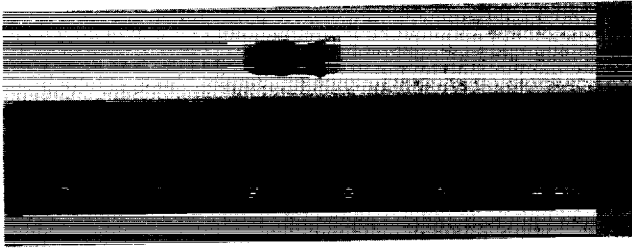


Figure 8.- Miniature IR proximity sensor.

sensors, a dexterous robotic hand would be capable of trapping an object by partially wrapping around it before coming into contact with it [8]. This will greatly increase the likelihood of success for the first grasp attempt. With these proximity sensors and the associated control system, the Utah/MIT hand is able to autonomously and securely grasp different shapes of objects and even catch objects tossed to it.

Control System

The EVAR Smart Hand control system development includes the design of servo control electronics using single-chip motor controllers, and the development of a VME bus based multi-processor control system using the Motorola 68020 32-bit microprocessors. The motor controller chip accepts encoder algorithm which resides on the chip itself. The execution of the control algorithm is invisible to the user, but the user has the ability to monitor the trajectory status and adjust the control parameters. Twelve motor controller chips fitted on a single PC expansion board that plugs into an IBM-XT motherboard have been used to control the Stanford/JPL hand. Since the trajectory of each motor is executed simultaneously by each motor controller chip independent of the host, the host central processing unit (CPU) is freed to execute other software routines. All high-level controls and some servo-level controls are accomplished by the VME bus based multi-processor control system using the 68020 microprocessors running the Software Components Group PSOS real-time operating system. A SUN 3/260 serves as the host for most control software development [9].

D. Derive an optimized EVAR Smart Hand design

Through the evaluations of the Utah/MIT hand, the Stanford/JPL hand, and the Direct Link Prehensor, the Direct Link Prehensor was found to have the most optimized finger arrangement, considering the trade-offs between complexity and functions. The anthropomorphic design of the Utah/MIT hand is desirable because it approximates an EVA crewmember's hand size and dexterity. But its remotizer and its large control electronics and actuator package make it enormously difficult to be packaged within the EVAR. The Stanford/JPL hand has fewer DOF than has the Utah/MIT hand, but its non-anthropomorphic design makes it difficult to share the same grasp interfaces as those used by an EVA crewmember. The Direct Link Prehensor has only 6 DOF in an anthropomorphic finger arrangement. This arrangement was found to be more adequate for grasping. Furthermore, the thumb is oriented

approximately 120 degrees from the index finger. This configuration also allows some manipulation capability. The capability of the Direct Link Prehensor to grasp in weightless environment was validated on a KC-135 aircraft zero-gravity experiment [7]. Based on the evaluations, the Direct Link Prehensor has been selected as the baseline configuration for the Phase II EVAR Smart Hand.

With the EVAR Smart Hand baseline configuration selected, a motorized version of this hand was built by NASA/JSC and named the Jameson hand after the designer of the Direct Link Prehensor and the Jameson hand - Dr. John Jameson. The Jameson hand, as shown in Figure 9, has an integrated hand-wrist-forearm package that approximates the combined size of a human hand, wrist, and forearm. There are seven DC motors packaged in the forearm, with one motor per each DOF, plus one that controls the tendon tension.

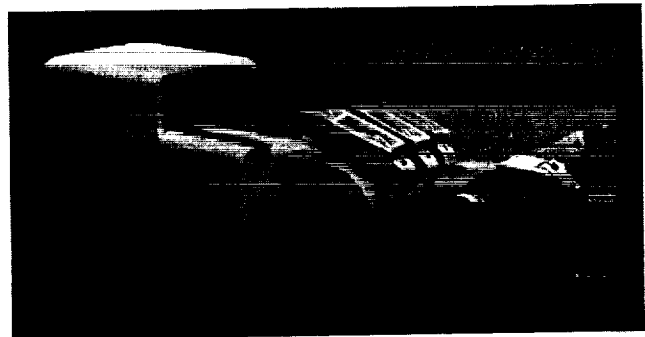


Figure 9.- Jameson hand.

The wrist on the Jameson hand comes from a remote RM-10A arm that is used on the EVAR. Power is transmitted from the motors through a tendon-pulley system to each joint, much like the remotizer in the Utah/MIT hand. This tendon-pulley system allows the hand to move freely with the wrist. The encoders on each motor and the strain gauges in the hand provide position and force feedback. Proximity sensors have been installed on the Jameson hand to provide autonomous adaptive grasping capability. The Jameson hand control system consists of servo motor controllers and the VME 68020 CPU's. The partition of tasks for parallel processing and the selection of motor controller chips for the Jameson hand control system were derived from the control system evaluations. The fabrication of the Jameson hand has been completed, and the software and the control system for the Jameson hand have been developed in the CTSD EVA Robotics Laboratory. The Jameson hand will be integrated with the EVAR in Phase II for dynamic evaluations.

E. Integrate prototype hand with EVAR ground demonstration

The EVAR ground demonstration system contains two NASA/JSC developed hands: the Jameson hand on the right arm of the EVAR, and the CTSD II hand on the left arm of the EVAR. The Jameson hand control

system CPU's and motor controllers are located inside the robot body. The power semiconductors which deliver current to the motors are packaged inside the forearm. The signal conditioning circuit for the CTSD II hand is located in the forearm. The motor controllers that control the CTSD II hand are contained in a small box mounted inside the robot body. Once the hands are mounted on the EVAR, the arm-hand coordination algorithms and the dynamic interactions between the robot body and the arms and hands will be evaluated. The Grasp Region Analysis Software Package (GRASP), a non-model based grasp software package developed by NASA/JSC to determine the proper grasp location based on 3D laser images, will be used to position the arms and hands. Figure 10 shows the Phase II EVAR ground demonstration system with the Jameson hand and the CTSD II hand.

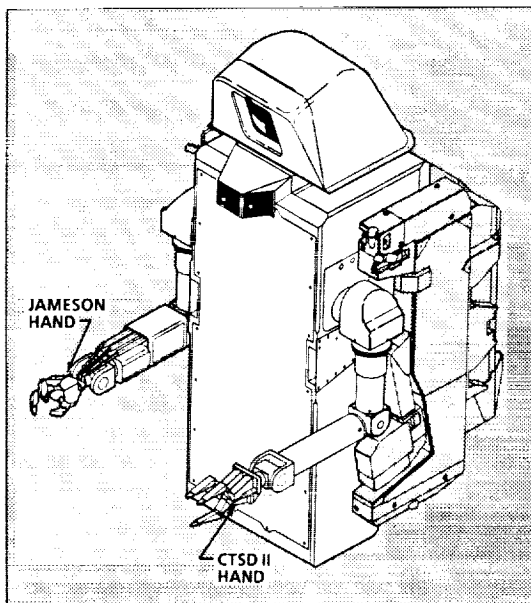


Figure 10.- EVAR Phase II hardware configuration.

FUTURE WORK

The development of EVAR Smart Hand is the first step in achieving the ultimate dexterous robotic hand capability. The next step is to develop autonomous manipulation capability. Pre-programmed robotic hand manipulations have been achieved through a teach-and-playback method. A more adaptive, real-time, intelligent, dexterous robotic hand manipulation capability will be pursued, using the Utah/MIT hand, the Stanford/JPL hand, and the Jameson hand as test beds. Dual-hand coordination will be evaluated by installing two dexterous hands on two robotic arms and selecting candidate tasks for evaluation. Tactile sensors will be evaluated and applied to the robotic hands to determine the contact locations and the directions of internal forces between the fingers and the object in order to provide adequate sensory feedback for intelligent robotic hand manipulation. Neural networks and other artificial intelligence software architectures will be explored for control and sensor fusion applications.

CONCLUSIONS

Several commercially available and in-house developed robotic hands have been evaluated for the development of the EVAR Smart Hand. The evaluations have shown that a dexterous robotic hand with 6 DOF in an anthropomorphic finger arrangement is sufficient for adaptive grasping. An autonomous, adaptive grasping concept was demonstrated on the Utah/MIT hand using position, force, and proximity sensors. The Jameson hand was developed with these features incorporated in a self-contained, hand-wrist-forearm package that approximates the combined size of a human hand, wrist, and forearm. The Jameson hand was designed to satisfy the objectives and the performance goals of the EVAR Smart Hand and will be integrated with the EVAR ground demonstration system in Phase II. Autonomous, robotic hand manipulation capability will be pursued in the follow-on efforts to develop a dexterous robotic hand system with capabilities approaching that of an EVA crewmember.

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